Application of Digital Image Processing in Wind Engineering

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1. Introduction

Low-speed velocity measurements found in thermally stratified flows are often difficult to measure by conventional techniques. Pressure type devices like Pitot-static tubes are not sensitive at speeds below 1 m/sec, hot-film and pulsed-wire anemometry is difficult to interpret in low-speed thermally stratified flows, and even expensive laser-doppler velocimetry require extra Bragg cell components and optical traversing equipment.

A smoke-wire method has been used at Colorado State in the past to evaluate the characteristics of low-speed thermally-stratified shear flows (Yamada 1971, Orgill 1973). In the smoke wire method, oil is evaporated from very thin, high-resistance nichrome wire by heating it with a high-voltage electric pulse from a capacitor discharge. A thin line of oil vapor is formed which is transported downwind by the local flow field. After a timed delay a strobe light illuminates the smoke line to record its behavior on photographic film. Photogrametry techniques are then used to retrieve smoke displacement, which is combined with the known time delay to specify the velocity field. Stereo-camera arrangements permit determination of all three velocity components. The accuracy of the velocity field is limited by inertia and buoyancy of the smoke vapor, photogrametric measurement reliability, and the limited number of realizations evaluated.

Digital image processing and image enhancement methods now provide a means to modernize and significantly improve the conventional smoke wire technique. The visible behavior of the smoke line is now recorded on by a high-resolution television camera system on VCR tape. The analog images may be transformed into digital arrays, and the images can then be enhanced and manipulated by a computer system. This paper will describe a relatively inexpensive digital image processing system developed to evaluate instantaneous, mean and rms velocity fields from smoke wire traces.

2. Video Image Analysis System

The hardware components of the Colorado State FDDL Video Image Processing System (VIPS) are noted in Figure 1. The image capturing part of the system includes a SVHS camcorder and a four-head one-half inch tape VCR recorder. These images may be edited into convenient sequences using a dual-monitor, dual-SVHS VCR recorder editing system. Unfortunately, most VCR systems cannot be controlled well enough to maintain adequate picture registration when advancing frame-by-frame under computer control (Lee et al., 1988). Hence, the edited VCR tape must be additionally recorded onto a video disk. Currently this transfer is being accomplished at another laboratory.

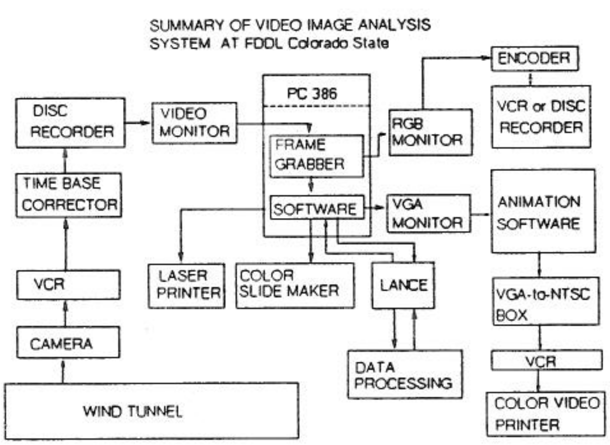

Figure 1 Video image analysis system

Computer control may be used to command a video-disk player to project each individual video frame to a high-resolution video monitor. We use a high-resolution image capturing board installed in a PC-386 compatible microcomputer to digitize the image. A standard NTSC video signal (30 frames/sec) can be digitized with 8-bit precision. The board we use produces an intensity field of 512 x 512 pixels at 256 possible gray levels. Given the image interweaving typical of an NTSC video signal the frames can be split to provide images at 60 frames/sec.

Once the video picture is digitized the image may be enhanced by a) subtracting the background, b) overlaying a coordinate system, c) enhancing front, center, or back edge of the image, or d) assigning colors to different intensity levels. As noted in the following section one can also extract edge pixel locations to calculate velocities, or combine images to provide animation.

Often it is appropriate to print or restore enhanced images. The FDDL VIPS includes hardware to project the image to a RGB or VGA monitor; store the digital image to floppy or hard disks, streaming tapes, optical digital disk, or on network file-servers; or print to a laser printer or color slide maker. Alternatively, a VGA-to-NTSC hardware card can reformulate the signal to record to a conventional VCR or a color video printer.

3. Processing of Smoke Wire Images

As noted above processing of the smoke wire images requires data acquisition followed by data reduction. Each smoke wire image is digitized and sequentially stored together with its time index in a data base. The image is digitized from left to right, top to bottom yielding a two-dimensional array of image pixels and intensities, P(i,j).

During data acquisition the digitized image is subtracted from a background image and the position of the smoke line enhanced by edge detection. Robert's edge detection operator described by Gonzales and Wintz (1987) was chosen to produce a single bright line. Robert's operator is

$$R[P(i,j)] = \text{Max}\ [\,|P(i,j)-P(i+1,j+1)|,|P(i+1,j) - P(i,j+1)|\,].$$

As soon as the position of the smoke line is determined the image is made uniformly bright by using a thresholding algorithm such as

$$B[P(i,j)] = \begin{cases} 1 & \text{if } R[P(i,j)] > T \\ 0 & \text{if } R[P(i,j)] < T, \end{cases}$$

where T is the threshold which defines the edge. A coordinate image taken in the same plane as the smoke pathlines may now be superimposed to improve registration of locations.

During data reduction a software program calculates local velocities from the new image data base. Two vertical sample lines, SL_1 and SL_2, may be designated in space downwind of the nichrome wire. The data base in then searched for the times, T_1 and T_2, that the SL pixel locations are turned on. Given $dX = X_{SL1} - X_{SL2}$, and $dT(x,y) = T_2(x+dx,y) - T_1(x,y)$, then the local velocity $U(x,y,t) = dX/dT$. Similar manipulations may provide values for local vertical velocities, $W(x,y,t)$.

Since many thousands of images may be obtained from a short TV tape record, it is possible to define average velocities as

$$U_{mean}(x,y) = \text{Avg }(U(x,y,t),$$

and the turbulence intensities as

$$\overline{u'^2}(x,y) = \text{Avg }([U(x,y,t) - U_{mean}(x,y)]^2).$$

4. Verification of Image Analysis Methodology

To validate hardware and software techniques described above simultaneous hot-film and smoke-wire measurements were made in the same turbulent boundary layer. Measurements were performed in the Meteorological Wind Tunnel of the Fluid Dynamics and Diffusion Laboratory for boundary layer developing over a rough floor 25 m downwind of the entrance at a wind speed of 0.5 m/sec. The flow produced a boundary layer 0.35 m deep with a power law index, α, of 0.21. Figure 2 presents a comparison between the two sets of measurements. One-thousand images of the smoke line were examined to create the average velocity and turbulent intensity profiles. Mean velocity and longitudinal turbulence profiles were identical within the statistical variability of the hot-film measurements.

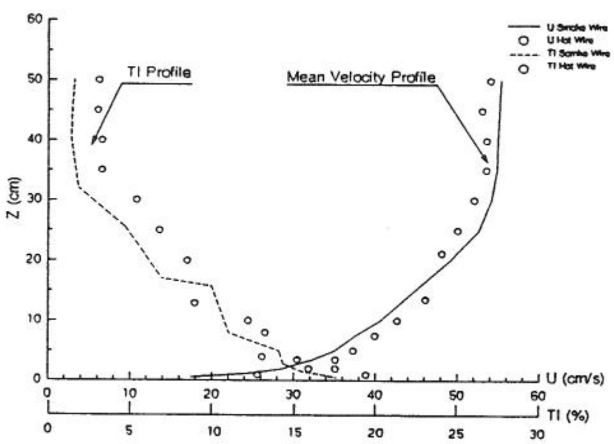

Figure 2 Boundary layer profiles of mean velocity and turbulence

5. Conclusions

Image analysis of smoke traces provide a powerful new method to analyze complex fluid motions, especially at low velocities in otherwise inconvenient thermally stratified environments. Once the smoke wire images are captured on video tape, much of the subsequent control of video hardware and data analysis may be completely automated.

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